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Blast Wave Hardening of Underwater Structures with Bubbly Water Layers

OCTOBER 1966

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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract No. AF 04(695)-1001.

This report, which documents research carried out form April 1962 through July 1966, was submitted on 18 October 1966 to Captain Robert F. Jones, SSTRT, for review and approval.

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Aerodynamics and Propulsion
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Publication of this report does not constitute Air Force Approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Robert F. Jones

Robert F. Jones, Capt. USAF
Space Systems Division
Air Force Systems Command

ABSTRACT

The attenuation of a blast wave passing through a layer of bubbly water is investigated under assumptions that permit an acoustic analysis. The presence of a small amount of air in water reduces the speed of sound drastically, often two orders of magnitude. For example, it is found that in a mixture of air and water at STP, the speed of sound is between 100 and 170 ft/sec for an air to mixture volume ratio of 5 to 15 percent. It is shown that this phenomenon can be used to harden underwater structures to fairly sizable compression waves (≈5000 psi) and to produce a possible order of magnitude reduction in the overpressure for a single bubble layer. Further attenuation may then be obtained by a sequence of bubble layers.

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NOMENCLATURE

c	sound speed
k	bulk modulus
ℓ	width of bubble layer along the x-axis
m	elemental mass
M	Mach number
P	pressure
$\mathfrak{R}$	Boltzmann gas constant
s	entropy
t	time
T	temperature
U	particle velocity
V	elemental volume
α	bubble volume per unit mixture volume
γ	specific heat ratio
λ	reflection coefficient
μ	air to water mass ratio
ρ	density
τ	ℓ/c

I. INTRODUCTION

In recent years a great deal of interest has been evinced in techniques for protection of underground or underwater structures from the severe environment such as could be produced by an atomic blast or a blast of conventional explosives. Most of the technology has centered around making a stronger structure rather than modifying the environment. The present work deals with a reduction of the blast wave before it reaches an underwater structure by means of a layer of bubbly water. It utilizes the fact that the presence of a small amount of air in water reduces the sound speed, c, drastically, often two orders of magnitude. Since the acoustic impedance is given by ρc, there is a significant impedance mismatch at the boundary between water and bubbly water. This fact can be used to reduce overpressures of 5000 psi or so to meaningful levels.

It is known[1,2] that the addition of a small amount of air (or other gas) to water produces a drastic change in the speed of sound in the mixture. For example, it is found that for a mixture of air and water at STP, the speed of sound is between 100 and 170 ft/sec for an air to mixture volume ratio of 5 to 15 percent. This compares with about 5000 ft/sec in water and about 1100 ft/sec in air. These phenomena have been verified experimentally as well as derived analytically[1,2,3].

It is shown in this paper that this phenomenon can be used to harden underwater structures to fairly sizable compression waves and to produce a possible order of magnitude reduction in the overpressure for a single bubble layer. Here attenuations are theoretically obtained for a single bubble layer; further attenuation of a water shock may be obtained then by a sequence of bubble layers placed before the site.

Since the properties of bubbly water are known, but not well disseminated, the following section presents a survey of the present status of bubbly water physics. Section III deals with the application of the results of Section II to attenuation of pulses. Section IV contains the conclusion of this study. The

principal assumption in the present work is that all analyses are essentially acoustic. Reference 3 is similar to the present work except that the acoustic assumptions are not made, and exact characteristic methods are used in Ref. 3. The simplicity of the acoustic assumptions make the present work easier to apply and make interpretation of the results more straightforward. Since Ref. 3 is more exact than the present work, it is heavily relied upon for comparisons.

II. PROPERTIES OF THE BUBBLY WATER

The speed of sound in a bubbly water mixture can easily be calculated, in first approximation, by assuming that an isothermal process takes place inside the individual bubble, that no heat is transmitted between the bubble and the water, that surface tension and viscosity can be neglected, and that there is no dynamic behavior of the bubble.

For an initial order of magnitude estimation of the effect of the mixture ratio on the sound speed,[1] consider a volume of bubbles, initially at a pressure P_0, and initially occupying a volume αV_0 where V_0 is the sample volume of bubbly water mixture, and α is the ratio of the initial bubble volume to the total sample volume. If a pressure rise ΔP is gradually imposed on the mixture, along with a concomitant volume change Δv, at constant temperature, then, neglecting the compressibility of the water, it follows that

$$(P_0 + \Delta P)(\alpha V_0 + \Delta v) = P_0 \alpha V_0 \quad . \tag{1}$$

If all changes of pressure and volume are considered to be infinitesimal, then Eq. (1) becomes

$$\Delta P = -(P_0/\alpha)(\Delta v/V_0) \quad . \tag{2}$$

Thus the bulk modulus is

$$k = P_0/\alpha \quad . \tag{3}$$

If the mass of the air can be neglected, the mixture density ρ is

$$\rho = \rho_w(1 - \alpha)$$

where ρ_w is the water density. The speed of sound is then given, approximately, in the range $0 < \alpha < 1$, by

$$c = \left(\frac{k}{\rho}\right)^{1/2} = \left[\frac{1}{\alpha(1 - \alpha)} \frac{P_o}{\rho_w}\right]^{1/2} \quad . \tag{4}$$

This analysis gives an infinite sound speed for $\alpha = 0$, $\alpha = 1$; this anomaly is due to the neglect of the compressibility of water and the density of air in first approximation. Equation (4) is plotted in Fig. 1 for $P_0 = 14.7$ psi, and

$$\rho_w = 1.93788 \frac{\text{lb sec}^2}{\text{ft}^4} \left(= \frac{62.4 \text{ lb/ft}^3}{32.2 \text{ ft/sec}^2}\right) \quad .$$

Table I gives the result of such a calculation.

For a more complete analysis, one can use the results of Parkin, Gilmore and Brode.[3] If one assumes that temperature changes in the water can be neglected during the heat flow occurring in the compression, and that the dynamic effects in the bubbles are of no consequence, one can derive an equation of state for the mixture

$$\frac{P}{T_a}\left[\frac{1 + \mu}{\mu\rho} - \frac{1}{\mu\rho^*(1 + P/k)}\right] = \frac{\mathfrak{R}}{m} \tag{5}$$

where μ is the ratio of the mass of air to the mass of water in a volume element and is given by

$$\mu = \frac{\alpha}{1 - \alpha} \frac{\rho_a}{\rho_w} \quad . \tag{6}$$

In Eqs. (3) and (6), P is the pressure, k is the bulk modulus of the water, T_a is the air temperature, ρ is the density of the mixture, ρ^* is the

water density at zero hydrostatic pressure, ρ_a is the air density, and ρ_w is the water density. To describe the equation of state of the air alone, it will be assumed to be a perfect gas:

$$\frac{P}{\rho_a T_a} = \frac{\mathcal{R}}{m} \quad . \tag{7}$$

For this report, the values $\rho^* = 1.93788$ lb-sec^2/ft^4, and $k = 3 \times 10^5$ psi will be used. The parameter μ can be obtained as a function of α, and is

$$\mu = \frac{Pm}{\mathcal{R}T_a} \frac{1}{\rho^*(1 + P/k)} \frac{\alpha}{1 - \alpha} \quad , \qquad 0 \le \mu \le \infty \quad . \tag{8}$$

Two cases are of interest in computing the speed of sound in the mixture; they are the isothermal bubble and the adiabatic bubble.

If the air-water mixture is initially in thermal equilibrium, then $T_a = T_w$. This temperature is assumed constant throughout the deformation. The speed of sound is given by $c^2 = (dP/d\rho)$. From Eqs. (5) and (7), one obtains

$$c_i^2 = \frac{P}{\rho}\left[1 - \frac{\rho}{(1 + \mu)\rho^*(1 + P/k)^2}\right]^{-1} \quad . \tag{9}$$

As is easily deduced, this speed of sound is least for $\alpha = 1/2$, which result is also obtained from Eq. (4).

If the process is assumed to be adiabatic, then the air is described by

$$\frac{dT_a}{T_a} = \frac{\gamma - 1}{\gamma} \frac{dP}{P} \tag{10}$$

where γ denotes the ratio of specific heats for air. From Eqs. (5), (7), and (10) one obtains:

$$c_a^2 = \frac{\gamma P}{\rho}\left[1 - \frac{\rho}{(1+\mu)\rho^*}\,\frac{1}{1+P/k}\left(1 - \frac{\gamma P/k}{1+P/k}\right)\right]^{-1} \quad . \tag{11}$$

These are plotted in Fig. 1 as functions of α for sea level, STP conditions. For low pressure $P/k \ll 1$, $0 < \alpha < 1$,

$$\left.\begin{aligned} &\frac{\rho_a}{\rho_w} \ll 1, \\ &c_i^2 \approx \frac{P}{\rho^*(1-\alpha)\alpha}\left(1 + \frac{\rho_a}{\rho_w}\right)^{-1}\left[1 + \alpha\,\frac{\rho_a^2/\rho_w^2}{1+\rho_a/\rho_w}\right], \text{ and} \\ &c_a^2 \approx \gamma c_i^2 \quad . \end{aligned}\right\} \tag{12}$$

For greater depths, the results are similar except that P increases (see Table II).

The above analysis will yield a fairly accurate value for the sound speed in bubbly water. It is based primarily upon static and quasi-stationary thermodynamics. There are, however, some additional effects, usually second order, that can be taken into account. For the purposes of this analysis and the acoustic assumptions used, these second order effects are of little importance; for completeness, they are mentioned below.

First, the bubbles will not behave in a quasi-static fashion when acted upon by a disturbance, but will have a dynamic response pattern of their own. Further, and probably more important, the thermodynamics of bubbles will be quite complicated, and allowance should be made for such higher order effects, as well as effects of reflected waves in the media, state changes due to waves passing through the medium, etc. It is estimated that for bubbles initially smaller than 0.01 in. in radius, the time required to cool to the

temperature of the water from a higher temperature is a few milliseconds.[3] For bubbles an inch or so in radius, the cooling times are so long that a reversible adiabatic process should be assumed. The latter conclusion is only valid so long as the bubbles do not break up.

Second, the problem of solubility should be considered. As pressure increases the solubility of air in water increases, and the bubbles will tend to dissolve. The solution times are generally greater than 10^{-2} sec for bubble radii greater than 10^{-3} in. and pressures less than 10^4 psi. For larger bubbles (1 in. radius) this time should be 1 sec.

To have a true shock wave in water alone, as differentiated from a simple compression wave, the overpressure should be of the order at 250,000 psi.[4] In order to assume that the acoustic approximations are valid in water, this analysis is limited to water overpressures of 20,000 psi. For this value of overpressure, $\rho_1/\rho_0 \leq 1.055$, and it is evident that any entropy jump across the wave[5] is negligible, and the shock can be replaced by a simple compression wave.

An analysis based upon stationary positioning of the different layers after incidence of the initial shock and subsequent reflection and transmittal of waves is a reasonable first approximation consistent with the neglect of various other small scale effects associated with an acoustic analysis. The medium 2 (see Fig. 2) is assumed to remain passive and homogeneous as the wave propagates through, and effects of local diffraction, local nonhomogeneous reflection, various irreversible processes, etc., are neglected in this first approximation. In the mixture region, the foregoing assumptions may be considered valid for $P_1 < 5000$ psi, hence acoustic methods will only be considered for this overpressure range in the mixture, although for water alone, such methods are clearly valid for $P_1 \approx 20,000$ psi. Detailed expressions for shock wave propagation in water[6] and bubbly mixtures[3] are in agreement, for lower overpressure ratios ($P_1 < 5000$ psi), with the results from the acoustic analysis presented here.

III. ATTENUATION OF BLAST WAVES

In this section, the possible uses of bubbly water to alleviate the effects of an atomic blast will be considered. An atomic blast in shallow water will have four main effects. First, there will be a shock wave generated in the water. It is expected that this will decay fairly rapidly into a simple compression wave ($P_1 \approx 5000$ psi) which may be treated by the acoustic approximation and which can be transmitted over fairly long distances. Secondly, there will be a "water wave" or tidal wave generated. Thirdly, a ground blast will be generated, and this will, of course, interact with the first two. Last, there will be an air blast wave generated, which is essentially the transmitted shock wave through the air-water interface.

This report is concerned primarily with the shock wave effect. The ground wave and the air wave have different effects and should be considered separately. The tidal wave will have long wavelengths (long compared with the dimensions of the bubbly water and/or the structure considered), and will depend on the parameters of the bomb and of the specific geometric configuration of the ocean bottom. The definition of the tidal wave problem with respect to these parameters is quite complicated and will not be considered here.

An actual shock wave in water implies an overpressure of the order of 250,000 psi.[4] It is felt that little can be done to harden a structure to such pressures. Accordingly, for purposes of this investigation, the pressure wave in the water will be considered to have an overpressure of 20,000 psi or less. For this range of pressure, the usual acoustic approximation will be valid in water, since $P/k \approx 0.067$. As mentioned in the previous section, in the air-water mixture, straightforward acoustic methods may be used with confidence for $P_1 \approx 5000$ psi; therefore, hardening will only be considered for this range of overpressures, although in water alone higher P_1 values may be treated by acoustic methods.

First, consider the blast wave propagating through an infinite layer of bubbly water. The situation is depicted schematically in Fig. 2, where the

source is assumed to be so far away that reflection from the source at A can be ignored. In medium (1), one has

$$\left.\begin{aligned} \frac{\partial^2 U_1}{\partial x^2} &= \frac{1}{c_1^2}\frac{\partial^2 U_1}{\partial t^2} \\ -\frac{\partial P_1}{\partial x} &= \rho_1 \frac{\partial U_1}{\partial t} \quad . \end{aligned}\right\} \tag{13}$$

Similarly, in medium (2), one has

$$\left.\begin{aligned} \frac{\partial^2 U_2}{\partial x^2} &= \frac{1}{c_2^2}\frac{\partial^2 U_2}{\partial t^2} \\ -\frac{\partial P_2}{\partial x} &= \rho_2 \frac{\partial U_2}{\partial t} \quad . \end{aligned}\right\} \tag{14}$$

In Eqs. (13) and (14), U_1 and U_2 are the velocities of the fluid particles in the two media, P_1 and P_2 are the pressures, and c_1 and c_2 are the sound speeds derived in Section II. The boundary conditions at the interface B are that $U_1 = U_2$, and $P_1 = P_2$. If an incident pressure pulse $P[t - (x/c_1)]$ is assumed to be incoming from the explosive source, then one can easily derive

$$\left.\begin{aligned} P_1 &= P\left(t - \frac{x}{c_1}\right) - (1 - \lambda) P_0\left(t + \frac{x}{c_1}\right) \\ P_2 &= \lambda P\left(t - \frac{x}{c_2}\right) \end{aligned}\right\} \tag{15}$$

where λ is the transmission coefficient given by

$$\lambda = \frac{2\,\dfrac{\rho_2 c_2}{\rho_1 c_1}}{1 + \dfrac{\rho_2 c_2}{\rho_1 c_1}} \quad . \tag{16}$$

The results are now simple to interpret. An initial pressure pulse $P_0(t)$ is attenuated into medium (2) with a strength $\lambda P(t)$. (It must be borne in mind that these are overpressures.) If the densities of the two media are assumed to be the same, and one takes $c_2 = 100$ ft/sec, $c_1 = 5000$ ft/sec, one has

$$\lambda = \frac{\dfrac{2}{50}}{1 + \dfrac{1}{50}} \approx \frac{1}{25} \quad . \tag{17}$$

This is an attenuation of a factor of 25. The greater attenuation will occur when $\alpha = 1/2$, and will be greater than this. The attenuation given by Eq. (22) reduces a blast wave of 5000 psi to one of 200 psi, a sizeable reduction.

Next, consider a bubble layer, illustrated by Fig. 3. Taking a Laplace transform, applying the boundary condition, and taking the incoming pulse in medium (1) as $P[t - (x/c_1)]$, one obtains

$$\begin{aligned} \overline{P}_3 &= \lambda(2 - \lambda)\,\overline{P}_0 \exp\left(-\frac{sz}{c_1}\right)\left[1 - (1 - \lambda)\exp(-2\tau_2 s)\right]^{-1} \\ &= \lambda(2 - \lambda)\,\overline{P}_0 \exp\left(-\frac{sz}{c_1}\right)\left[1 + (1 - \lambda)^2 \exp(-2\tau_2 s) + (1 - \lambda)^4 \exp(-4\tau_2 s)\right] \end{aligned} \tag{18}$$

where $\tau_2 = \ell_2/c_2$. Each term in the series contained in the braces represents a reflection from C to B and back to C into medium (3) again. Thus,

$$\left. P_3 = \lambda(2 - \lambda)\left[P_0\left(\tau - \frac{z}{c_1}\right) + (1 - \lambda)^2 P_0\left(\tau - 2\tau_2 - \frac{z}{c_1}\right) + (1 - \lambda)^4 P_0\left(\tau - 4\tau_2 - \frac{z}{c_1}\right) + \ldots\right] \right\} \tag{19}$$

where $\tau = t - \tau_2$.

In this case, the attenuation is not quite as straightforward to determine as before. The pulse P_0 will possess a width, say τ_0. If it is less than $2\tau_2$, then a point z will see a series of separate pulses as shown in Fig. 4. Each succeeding pulse is attenuated from the original transmitted pulse by a factor of $(1 - \lambda)^2$, $(1 - \lambda)^4$, etc. The original attenuation of $(2 - \lambda)$ multiplies the entire expression. If, however, $\tau_0 > 2\tau_2$, then the situation is as shown in Fig. 5. Each reflected pulse catches up with the preceding one for some portion of its width. It is conceivable that these reflected pulses could even add up to a pulse greater than the original pulse. In any event, the spacing of the bubble layer should be adjusted to avoid these additive reflections. Periods for blast pulses for lower energy explosions have been given;[6] however, for the energies considered in underwater nuclear blasts, data is not available to the authors at present, nor is data on the width and shape of blast pulses. The simplifying assumption of a plane shock of infinitesimal thickness is used throughout this analysis; a more detailed approach must necessarily use the entire pulse shape behind the steep fronted initial portion of the wave.

Next, consider a rigid wall protected by a bubble layer. The geometry is as in Fig. 3 except that medium (3) is now a rigid wall. The solution for the pressure at the interface C is now

$$\overline{P}_c = 2\lambda\overline{P}_0 \exp(-s\tau_2)[1 - (1 - \lambda)\exp(-2s\tau_2)]^{-1} \tag{20}$$

The term $\exp(-s\tau_2)$ represents the time the original disturbance takes to reach the wall C. Measuring time from this point, $\tau = t - \tau_2$, eliminates this factor. Thus:

$$\overline{P}_c = 2\lambda\overline{P}_0[\,1 + (1 - \lambda)\exp(-2s\tau_2) + (1 - \lambda)^2\exp(-4s\tau_2) + \ldots\,] \quad (21)$$

The situation is identical to the preceding one except that each successive pulse is attenuated by the factor $(1 - \lambda)$ instead of $(1 - \lambda)^2$. The inversion of (21) gives

$$P_c = 2\lambda[\,P_0(\tau) + (1 - \lambda)P_0(\tau - 2\tau_2) + (1 - \lambda)^2P_0(\tau - 4\tau_2) + \ldots\,] \quad (22)$$

Both principal attenuations $\lambda(2 - \lambda)$ and 2λ are of the order of 1/12.5, which is at least one order of magnitude (assuming $c_2 \approx 100$ ft/sec, $c_1 \approx 5000$ ft/sec).

There are other configurations of interest, such as multiple layers, and curved layers that can be investigated, but since this is a preliminary analysis it is not deemed necessary to do so.

For pressures of the order of $P_1 \approx 4000$ psi, attenuations predicted here and those given in Ref. 3 are comparable. For higher pressures Ref. 3 assumes the acoustic approximation to hold provided the local sound speeds in (2) are adjusted due to the passage of the initial pressure and reflected waves through (2). For the lower pressures ($P_1 < 4000$ psi) the medium is essentially passive and the wave has small effect on the sound speed change, so that the simple acoustic approximation is applicable in the usual sense. In Ref. 3, for $P_1 \approx 10,000$ psi, attenuations are small due to the fact that the passage of the wave increases sound speed to near that of pure water. The reflected wave of small intensity is then practically repropagating through pure water; i.e., the initial wave propagates into a region of the same acoustic impedance as that behind the wave. The possibility of the bubble mixture undergoing phase changes, the collapse of the bubbles to vanishingly small radius as the wave propagates through, and the resulting

effect on wave propagation phenomena and reflection phenomena, make the applicability of acoustic methods seem somewhat limited even with local impedance changes within (2) governing various strength waves propagating through (2). Reference 3 requires the assumption of thin bubble layer thickness to hold so that the wave may be considered as a plane shock in (2). Hence, limitations of a higher order of complexity limit the present analysis to overpressures $P_1 \approx 5000$ psi and thin bubble sheets. Considerable attenuation is obtained both in Ref. 3 and the present analysis by the addition of a bubble layer. The confirmation of the results of Ref. 3 for $P_1 \approx 5000$ psi implies a workable method for attenuation; for higher pressures, the mechanisms and wave models must necessarily be subject to experiment to obtain reliable results, as the acoustic approximation in a nonpassive medium is open to question. Therefore, it is the conclusion of this paper that a bubble layer, or a sequence of layers, is sufficient to attenuate a water shock wave of $P_1 \approx 5000$ psi by one or more orders of magnitude. Further attenuations for higher P_1 values must be determined by consideration of more complex wave phenomena beyond the scope of this preliminary report.

IV. CONCLUSIONS AND RECOMMENDATIONS

It has been shown in this paper that a layer of bubbles can reduce the overpressure of a shock wave in water by an order of magnitude for a single layer. For multiple layers, the attenuation could be considerably greater.

Much of the groundwork for a practical study of such a method of hardening sites has been done.[3] Many important problems such as the diffraction of a shock wave by a bubble layer surrounding an obstacle, and others mentioned here, are left unanswered. It is felt, however, that the main need is for experimental work to verify the theory of bubbly mixtures, to verify the computed attenuation for the acoustic approximation given here, and to determine the limit of extension of the acoustic approximation to higher overpressures. Additional experiments for more complex nonlinear wave models and separation distances are also clearly indicated as further extensions of this hardening concept.

FOOTNOTES

1. I. J. Campbell, and A. S. Pitcher, Proc. Roy. Soc. (London), Ser. A, 234, 534 (1958).

2. R. F. Tangren, C. H. Dodge, and H. S. Siefert, J. Appl. Phys., 20, 637, (1944).

3. B. R. Parkin, F. R. Gilmore, and H. L. Brode, RM-2795-PR (Abridged), Rand Corporation Memorandum, (October 1961).

4. H. P. Stanyukovich, Unsteady Motion of Continuous Media, (Pergamon Press, New York, 1960).

5. The subscripts 0 and 1 refer to conditions before and behind the shock, respectively.

6. R. Cole, Underwater Explosions, (Princeton University Press, 1948).

Table I. c vs α for STP

α	c ft/sec (Calculated)	c ft/sec (Measured)[1]
0.05	151.6	150
0.1	110.2	128
0.15	92.70	95
0.2	82.62	141
0.25	76.31	80

Table II. c vs α for the Isothermal and the Adiabatic Case at Sea Level and 100 ft below Sea Level

α	Sea Level		100 Feet	
	c_1	c_a	c_i	c_a
0.05	151.5	179.2	300.9	355.6
0.1	110.0	130.1	218.5	258.4
0.15	92.05	108.9	182.8	216.3
0.2	82.57	97.68	164.0	194.0
0.25	76.27	90.25	151.5	179.2

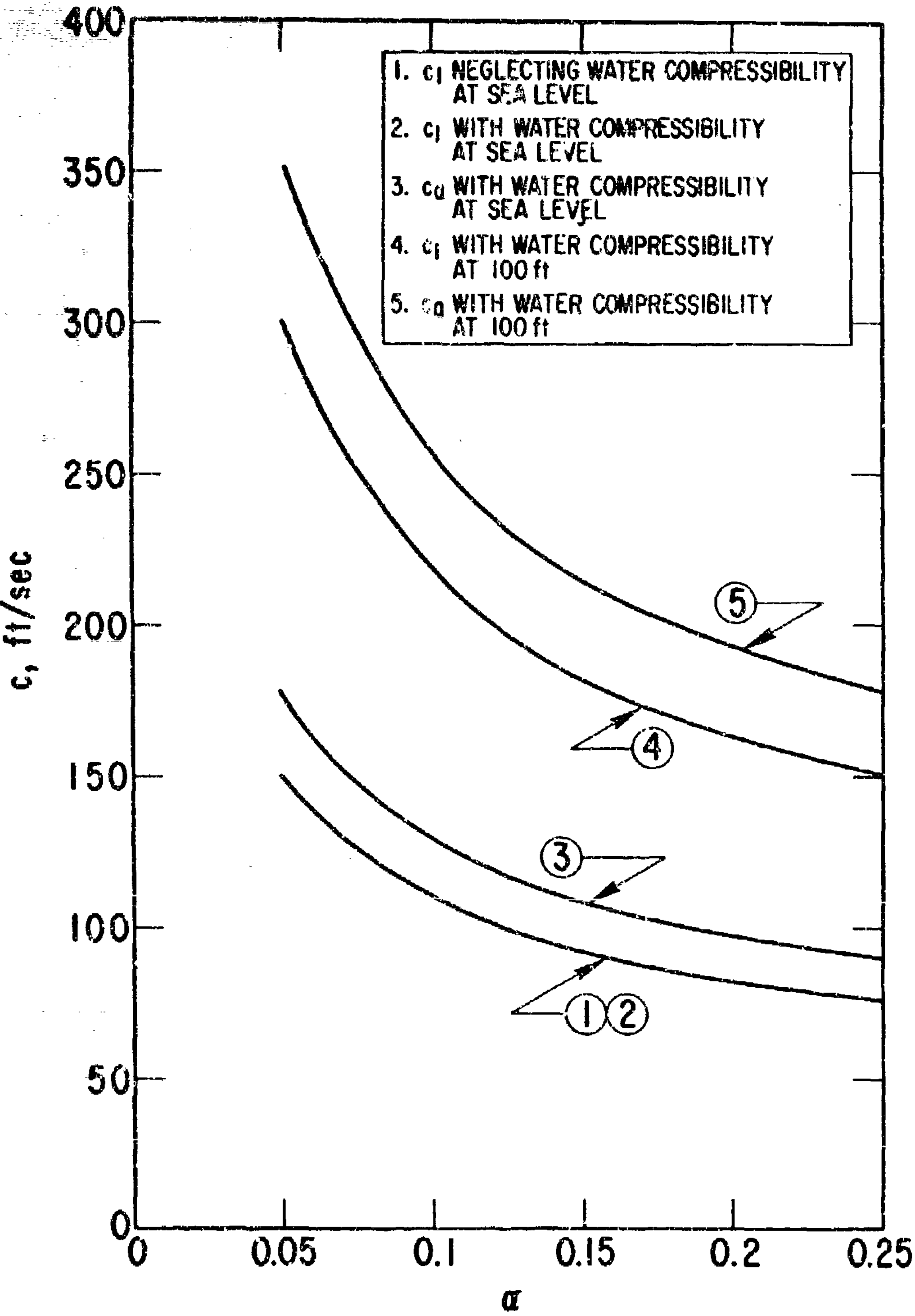

Fig. 1. c vs α for a Bubble Mixture

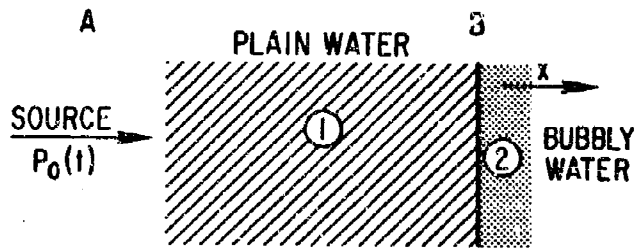

Fig. 2. Bubble Layer Geometry

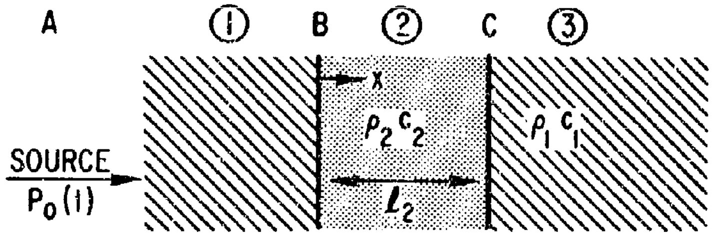

Fig. 3. A Bubble Layer

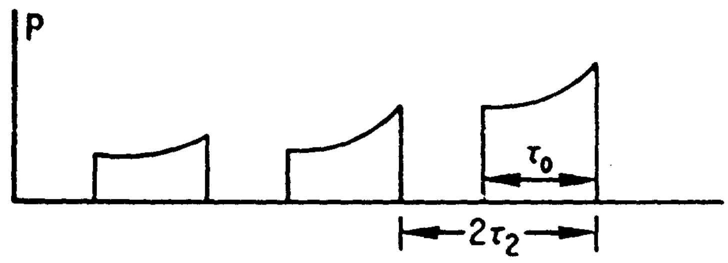

Fig. 4. **Pulse Transmission** $\tau_0 < 2\tau_2$

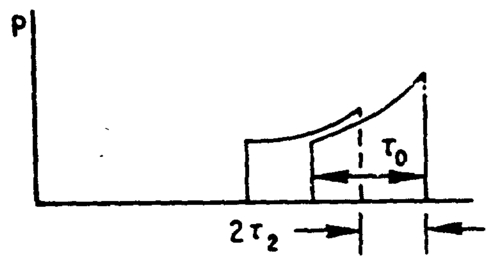

Fig. 5. Pulse Transmission
$\tau_0 > 2\tau_2$

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13 ABSTRACT

The attenuation of a blast wave passing through a layer of bubbly water is investigated under assumptions that permit an acoustic analysis. The presence of a small amount of air in water reduces the speed of sound drastically, often two orders of magnitude. For example, it is found that in a mixture of air and water at STP, the speed of sound is between 100 and 170 ft/sec for an air to mixture volume ratio of 5 to 15 percent. It is shown that this phenomenon can be used to harden underwater structures to fairly sizable compression waves (≈5000 psi) and to produce a possible order of magnitude reduction in the overpressure for a single bubble layer. Further attenuation may then be obtained by a sequence of bubble layers.

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14. KEY WORDS
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Underwater hardening
Vulnerability
Blast wave attenuation

Abstract (Continued)

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